

The anomalous top quark coupling tqg and tW production at the LHC

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Abstract

Many new physics models beyond the standard model (SM) can give rise to the large anomalous top couplings tqg ($q = u$ and c). We focus our attention on these couplings induced by the topcolor-assisted technicolor ($TC2$) model and the littlest Higgs model with T -parity (called LHT model), and consider their contributions to the production cross section and the charge asymmetry for tW production at the LHC . We find that the anomalous top coupling tqg induced by these two kinds of new physics models can indeed generate sizable charge asymmetry. The correction effects of the LHT model on the production cross sections of the processes $pp \rightarrow tW^- + X$ and $pp \rightarrow \bar{t}W^+ + X$ are significant large, which might be detected at the LHC .

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1. Introduction

One of the main goals of the current or future high energy experiments, such as the *LHC* and *ILC*, is to search for new physics beyond the standard model (*SM*) [1]. Because of the largest mass of the top quark among all observed particles within the *SM*, it may be more sensitive to new physics than other fermions and it may serve as a window to probe new physics. Thus, studying the correction effects of new physics on observables about top quark is a good way to test the *SM* flavor structure and to learn more about the nature of electroweak symmetry breaking (*EWSB*) [2].

In the *SM*, top quark can be produced singly via electroweak interaction at hadron colliders. At leading order, there are three kinds of the partonic processes: the s-channel process ($q'\bar{q} \rightarrow tb$) involving the exchange of a time-like W boson, the t-channel process ($bq \rightarrow tq'$) involving the exchange of a space-like W boson, and the tW production process ($gb \rightarrow tW^-$) involving an on-shell W boson. These processes have completely different kinematics and can be observed separately [2]. Furthermore, the t-channel process is the main source of single top production, both at the *Tevatron* and the *LHC*. At the *Tevatron*, the contributions of the tW production process are very small, while the contributions from the s-channel production process are very small at the *LHC*. Thus, an accurate description of all the three production processes is important.

tW production at hadron colliders has been calculated at next leading order (*NLO*) in the *SM* [3] and been extensively studied in Refs.[4, 5]. It has been shown that this process is observable at the *LHC* using the fully simulated data at the *CMS* and *ATLAS* detectors [6, 7]. In the *SM*, the tW production channel is charge symmetric, which means that the production cross section for the process $pp \rightarrow tW^- + X$ is equal to that for the process $pp \rightarrow \bar{t}W^+ + X$. However, the charge asymmetry in the tW production process can be generated by non-*SM* values of V_{td} and V_{ts} of *CKM* matrix [8] and by the anomalous top coupling tqg ($q = u$ or c) [9].

In the *SM*, the anomalous top quark coupling tqg is absent at tree level and is extremely suppressed at one loop due to the *GIM* mechanism [10], which can not be de-

tected in current or future high-energy experiments. However, it may be large in some new physics models beyond the SM , such as the topcolor-assisted technicolor ($TC2$) model [11, 12], the littlest Higgs model with T -parity (called LHT model) [13], etc. In this paper, we will focus our attention on the anomalous top couplings induced by the $TC2$ model and the LHT model, and calculate their contributions to the production cross section and the charge asymmetry for tW production at the LHC with the center-of-mass ($c.m.$) energy $\sqrt{s} = 14TeV$. Our numerical results show that the contributions of the anomalous top coupling tqg induced by the $TC2$ model to the tW process are generally smaller than those for the LHT model. With reasonable values of the free parameters of the LHT model, its corrections to the production cross sections of the processes $pp \rightarrow tW^- + X$ and $pp \rightarrow \bar{t}W^+ + X$ are in the ranges of $14\% \sim 32\%$ and $11\% \sim 24\%$, respectively. The value of the charge asymmetry parameter $R = \sigma(tW^-)/\sigma(\bar{t}W^+)$ can reach 1.05.

After discussing the anomalous top couplings tqg induced by the $TC2$ model and the LHT model, we calculate the additional contributions of these anomalous top couplings to the tW production channel at the LHC in sections 2 and 3. Our conclusions are given in section 4.

2. The $TC2$ model and tW production at the LHC

The $TC2$ model [11] is one of the phenomenologically viable models, which has almost all essential features of the topcolor scenario [12]. This model has two separate strongly interacting sectors in order to explain $EW\!SB$ and the large top mass. Technicolor interaction is responsible for most of $EW\!SB$ via the condensation of technifermions, but contributes very little to the top mass εm_t with the parameter $\varepsilon \ll 1$. The topcolor interaction generates the bulk of m_t through condensation of top pairs $\langle t\bar{t} \rangle$, but makes only a small contribution to $EW\!SB$.

The $TC2$ model predicts the existence of a number of new scalar states at the electroweak scale: three top-pions (π_t^\pm, π_t^0), a top-Higgs (h_t^0), and a techin-Higgs (h_{tc}^0), which are bound-states of the top quark, the bottom quark and of the techin-fermions. Since

the topcolor interaction is not flavor-universal and mainly couples to the third generation fermions, the couplings of top-pions or top-Higgs to the three family fermions are non-universal, and they have large *Yukawa* couplings to the third generation and can induce flavor changing (*FC*) couplings. The couplings of the top-pions (π_t^0, π_t^\pm) to ordinary fermions, which are related to our calculation, can be written as [11, 12, 14]

$$\frac{m_t}{\sqrt{2}F_t} \frac{\sqrt{\nu_W^2 - F_t^2}}{\nu_W} (iK_{UL}^{tt*} K_{UR}^{tt} \bar{t}_L t_R \pi_t^0 + \sqrt{2} K_{UR}^{tt*} K_{DL}^{bb} \bar{t}_R b_L \pi_t^+ + \quad (1)$$

$$iK_{UL}^{tt*} K_{UR}^{tc} \bar{t}_L c_R \pi_t^0 + \sqrt{2} K_{UR}^{tc*} K_{DL}^{bb} \bar{c}_R b_L \pi_t^+ + h.c.), \quad (2)$$

where $\nu_W = \nu/\sqrt{2} \approx 174 GeV$, $F_t \approx 50 GeV$ is the physical top-pion decay constant, which can be estimated from the Pagels-Stokar formula. To yield a realistic form of the *CKM* matrix V_{CKM} , it has been shown that the values of the matrix elements $K_{UL(R)}^{ij}$ can be taken as [14]

$$K_{UL}^{tt} \approx K_{DL}^{bb} \approx 1, K_{UR}^{tt} \approx 1 - \varepsilon, K_{UR}^{tc} \leq \sqrt{2\varepsilon - \varepsilon^2}. \quad (3)$$

In the following numerical estimation, we will assume $K_{UR}^{tc} = \sqrt{2\varepsilon - \varepsilon^2}$ and take ε as free parameter.

The relevant couplings for the top-Higgs h_t^0 are similar with those of the neutral top-pion π_t^0 [14]. However, the coupling $h_{tc}^0 t\bar{t}$ is very small, which is proportionate to a factor of $\varepsilon/\sqrt{2}$ [15]. Furthermore, the mass of the techni-Higgs h_{tc} is at the order of $1 TeV$. Thus, the contributions of h_{tc} to the tW production process can be safely neglected.

From the above discussions we can see that the neutral top-pion π_t^0 and the top-Higgs h_t^0 can generate the anomalous top coupling vertex $t\bar{c}g$, which are shown in *Fig.1*. It is obvious that the effective vertex tcg can generate additional contributions to the tW production channel at the *LHC*. The relevant Feynman diagrams are shown in *Fig.2*.

Certainly, the neutral scalars π_t^0 and h_t^0 can also generate the anomalous top coupling vertex $t\bar{u}g$ via the *FC* couplings $\pi_t^0(h_t^0)t\bar{u}$. However, it has been argued that the maximum *FC* mixing occurs between the third and second generation fermions, and the *FC* couplings $\pi_t^0(h_t^0)t\bar{u}$ is very small which can be neglected [14]. Similar to π_t^0 , the charged

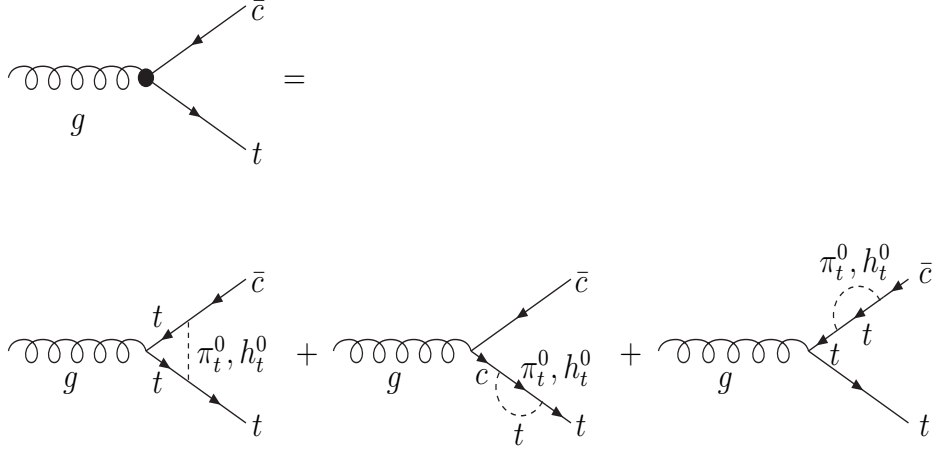


Figure 1: Feynman diagrams for the effective vertex $t\bar{c}g$ in the TC2 model.

top-pions π_t^\pm can also give rise to the anomalous top coupling tcg via the FC couplings $\pi_t^\pm bc$. However, compared with those of π_t^0 , the contributions of π_t^\pm to the tcg coupling are approximately suppressed by the factor m_b^2/m_t^2 , which can be safely neglected. Hence, in the following numerical estimation, we will ignore the contributions of π_t^\pm to the tW production process.

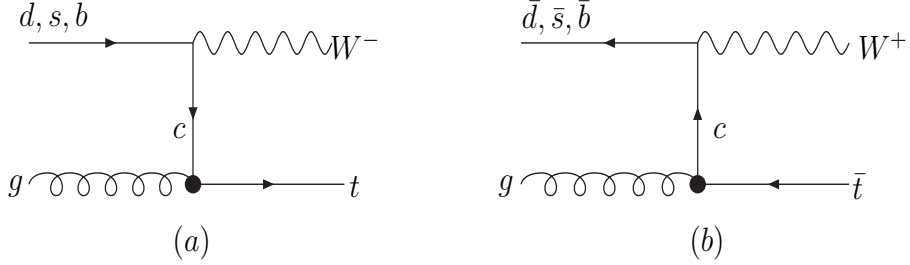


Figure 2: Feynman diagrams for the tW production process at the LHC contributed by the anomalous top coupling tcg .

One of the authors for this paper has discussed the anomalous top coupling tcg induced by the $TC2$ model in Ref.[16]. The explicit expressions for the effective vertex $t\bar{c}g$ has

been given in Ref.[16]. In this paper, we will use *LoopTools* [17] and the *CTEQ6L* parton distribution functions (*PDFs*) [18] to calculate the contributions of the *TC2* model to the tW production process. The renormalization and factorization scales (μ_R and μ_F) have been taken equal to $\mu_F = \mu_R = m_t + m_W$. The masses of the top quark and the gauge boson W are taken as $m_t = 170.9\text{GeV}$ and $m_W = 80.42\text{GeV}$ [19]. It is obvious that the cross sections for the processes $pp \rightarrow tW^- + X$ and $pp \rightarrow \bar{t}W^+ + X$ are dependent on the free parameter ε and the masses of the top-pion and top-Higgs boson. From the theoretical point of view, ε with value from 0.01 to 0.1 is favored [11]. In this paper we will assume that its value is in the range of $0.03 \sim 0.08$. The masses of the neutral top-pion and top-Higgs boson are model-dependent and are usually of a few hundred GeV [12]. In our numerical estimation, we will take $m_{\pi_t^0} = m_{h_t^0} = M$ and assume that the value of M is in the range of $200\text{GeV} \sim 500\text{GeV}$.

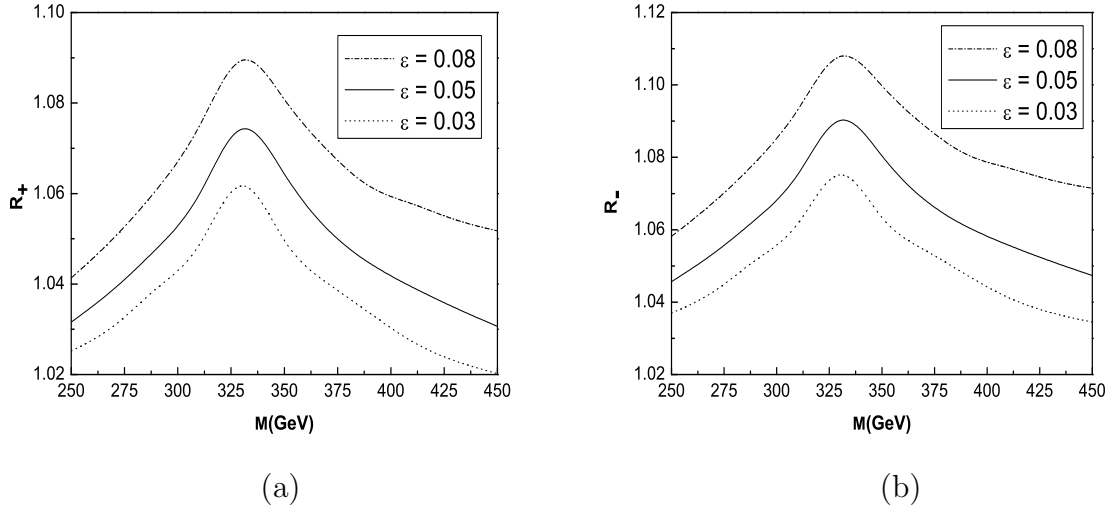


Figure 3: The relative correction parameters $R_+(a)$ and $R_-(b)$ as function of the mass parameter M for three values of the parameter ε .

To see whether the contributions of the anomalous top coupling tcg induced by the *TC2* model to the tW production channel can be detected at the *LHC*, we define the relative correction parameters as

$$R_+ = \frac{\sigma(\bar{t}W^+)}{\sigma^{SM}(\bar{t}W^+)}, \quad R_- = \frac{\sigma(tW^-)}{\sigma^{SM}(tW^-)}, \quad (4)$$

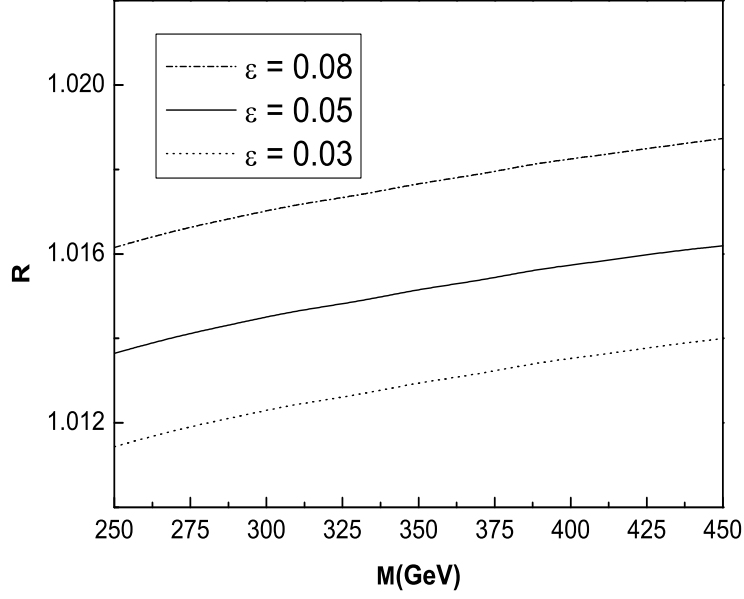


Figure 4: The charge asymmetry parameter R as a function of M for the parameter $\varepsilon = 0.03, 0.05$ and 0.08 .

where $\sigma(\bar{t}W^+)$ and $\sigma(tW^-)$ denote the total production cross sections including the contributions from the SM and the $TC2$ model for the processes $pp \rightarrow \bar{t}W^+ + X$ and $pp \rightarrow tW^- + X$, respectively. The charge asymmetry parameter R is defined as $R = \sigma(tW^-)/\sigma(\bar{t}W^+)$. Since the PDF for the bottom quark in proton is same as that for the anti-bottom quark, there is $R = 1$ in the SM .

Our numerical results are summarized in *Fig.3* and *Fig.4*, in which we plot the parameter R_i as function of the mass parameter M for the $c.m.$ energy $\sqrt{s} = 14TeV$ and three values of the free parameter ε . One can see from *Fig.3* that there is a peak at $M \sim 330GeV$, which is due to the effect of the $t\bar{t}$ in the loop going on-shell and the anomalous top coupling tcg increasing. In all of the parameter space of the $TC2$ model, the value of R_+ is smaller than that of R_- and the value of the parameter R is larger than 1, which leads to an charge asymmetry for the tW production process. For $0.03 \leq \varepsilon \leq 0.08$ and $200GeV \leq M \leq 500GeV$, the corrections to the production cross sections of the

processes $pp \rightarrow \bar{t}W^+ + X$ and $pp \rightarrow tW^- + X$ are in the ranges of $2.5\% \sim 5.2\%$ and $3.7\% \sim 7.2\%$, respectively. The value of the charge asymmetry parameter R is in the range of $1.011 \sim 1.018$. It has been shown [6, 7] that the production cross section of tW production at the LHC can be measured with precision of about 9.9% and 2.8% for $10fb^{-1}$ and $30fb^{-1}$ of integrated luminosity of data, respectively. Thus, it is impossible to detect the charge asymmetry induced by the $TC2$ model for the tW production process at the LHC even for the $c.m.$ energy $\sqrt{s} = 14TeV$.

3. The LHT model and tW production at the LHC

Little Higgs theory [20] was proposed as an alternative solution to the hierarchy problem of the SM , which provides a possible kind of $EWSB$ mechanism accomplished by a naturally light Higgs boson. In order to make the littlest Higgs model consistent with electroweak precision tests and simultaneously having the new particles of this model at the reach of the LHC , a discrete symmetry, T -parity, has been introduced, which forms the LHT model. The detailed description of the LHT model can be found for instance in Refs.[13, 21, 22], and here we just want to briefly review its essential features, which are related to our calculation.

The LHT model is based on an $SU(5)/SO(5)$ global symmetry breaking pattern. A subgroup $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$ of the $SU(5)$ global symmetry is gauged, and at the scale f it is broken into the SM electroweak symmetry $SU(2)_L \times U(1)_Y$. T -parity exchanges the $[SU(2) \times U(1)]_1$ and $[SU(2) \times U(1)]_2$ gauge symmetries. The T -even combinations of the gauge fields are the SM electroweak gauge bosons W_μ^a and A_μ . The T -odd combinations are T -parity partners of the SM electroweak gauge bosons.

After taking into account $EWSB$, at the order of v^2/f^2 , the masses of the T -odd set of the $SU(2) \times U(1)$ gauge bosons are given as

$$M_{A_H} = \frac{g_1 f}{\sqrt{5}} \left[1 - \frac{5v^2}{f^2} \right], \quad M_{Z_H} \approx M_{W_H} = g_2 f \left[1 - \frac{v^2}{8f^2} \right], \quad (5)$$

where $v = 246GeV$ is the electroweak scale and f is the scale parameter of the gauge symmetry breaking of the LHT model. g_1 and g_2 are the SM $U(1)_Y$ and $SU(2)_L$ gauge

coupling constants, respectively.

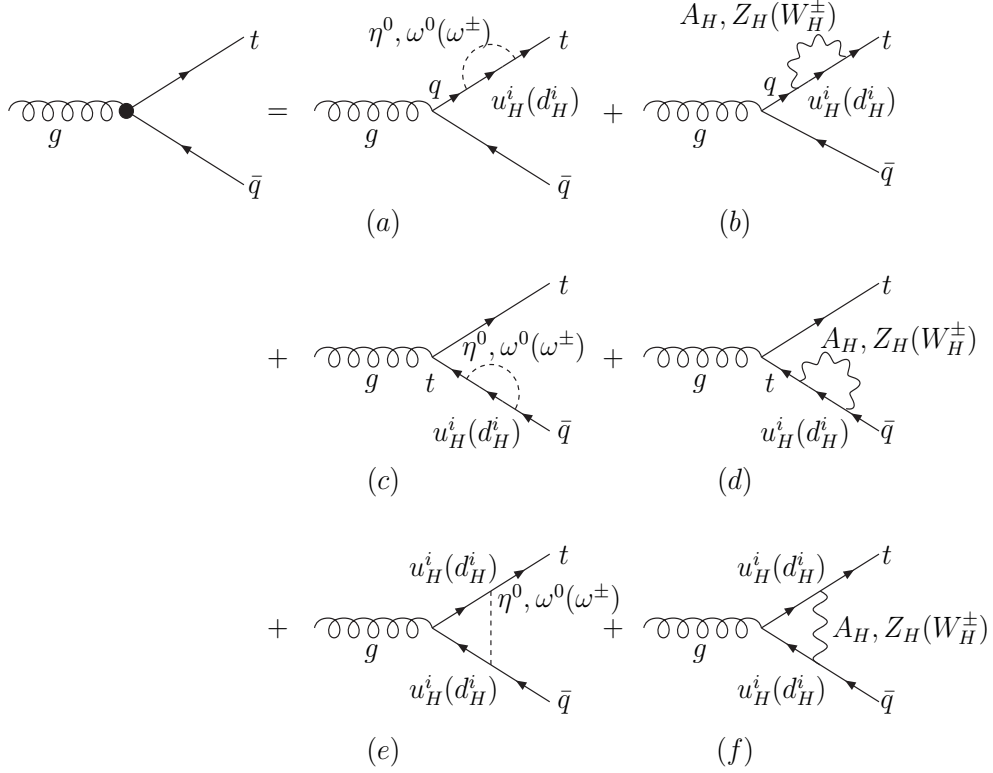


Figure 5: Feynman diagrams for the effective vertex $t\bar{q}g$ in the LHT model.

A consistent implementation of T -parity also requires the introduction of mirror fermions — one for each quark and lepton species. The masses of the T -odd (mirror) fermions can be written in a unified manner

$$M_{F_i} = \sqrt{2}k_i f, \quad (6)$$

where k_i are the eigenvalues of the mass matrix k and their values are generally dependent on the fermion species i . These new fermions (T -odd quarks and T -odd leptons) have new FC interactions with the SM fermions. These interactions are governed by new mixing matrices V_{Hd} and V_{Hl} for down-type quarks and charged leptons, respectively. The corresponding matrices in the up-type quarks (V_{Hu}) and neutrino ($V_{H\nu}$) sectors are obtained by means of the relations

$$V_{Hu}^+ V_{Hd} = V_{CKM}, \quad V_{H\nu}^+ V_{Hl} = V_{PMNS}. \quad (7)$$

Where the CKM matrix V_{CKM} is defined through flavor mixing in the down-type quark sector, while the $PMNS$ matrix V_{PMNS} is defined through neutrino mixing.

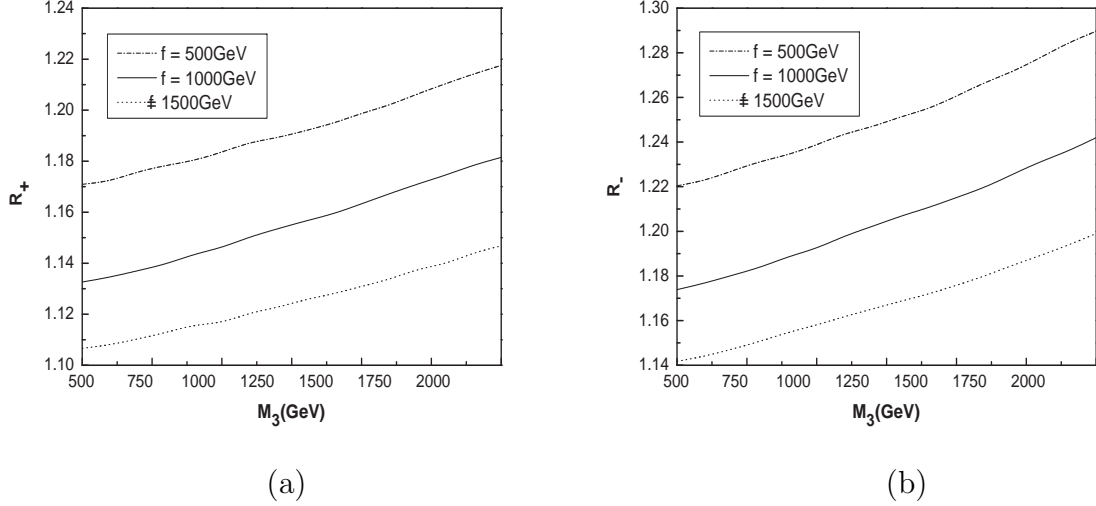


Figure 6: In case I, the parameters $R_+(a)$ and $R_-(b)$ dependence on the mass parameter M_3 for $M_1 = M_2 = 300\text{GeV}$ and three values of the scale parameter f .

The Feynman rules of the LHT model have been studied in Ref.[22] and the corrected Feynman rules of Ref.[22] are given in Refs.[23, 24]. To simplify our paper, we do not list them here.

From the above discussions, we can see that the flavor structure of the LHT model is much richer than the one of the SM , mainly due to the presence of three doublets of mirror quarks and leptons and their interactions with the ordinary quarks and leptons, which are mediated by the T -odd gauge bosons (A_H , W_H^\pm , and Z_H) and Goldstone bosons (η_0 , ω_0 , and ω^\pm). Such new FC interactions can induce the anomalous top coupling tqg ($q = c$ and u) in quark sector. The relevant Feynman diagrams for the effective vertex $t\bar{q}g$ are shown in *Fig.5*. To simplify our paper, we do not give the analytical expressions of the effective vertexes $t\bar{c}g$ and $t\bar{u}g$ here. The new coupling tqg can generate significant contributions to the FC top decays $t \rightarrow cg$, $t \rightarrow c\bar{q}g$ and the FC single top production processes $pp \rightarrow \bar{t}c + X$, $pp \rightarrow t + X$, and $pp \rightarrow tg + X$ [25]. In this section, we will

consider its contributions to tW production at the LHC . Similar with section 2, we use the *LoopTools* [17] to give our numerical results in the ' t *Hoof*t-Feynman gauge. In our calculation, we use the corrected Feynman rules including the high order ν^2/f^2 terms and neglect the terms proportioning to m_c/m_t or m_u/m_t .

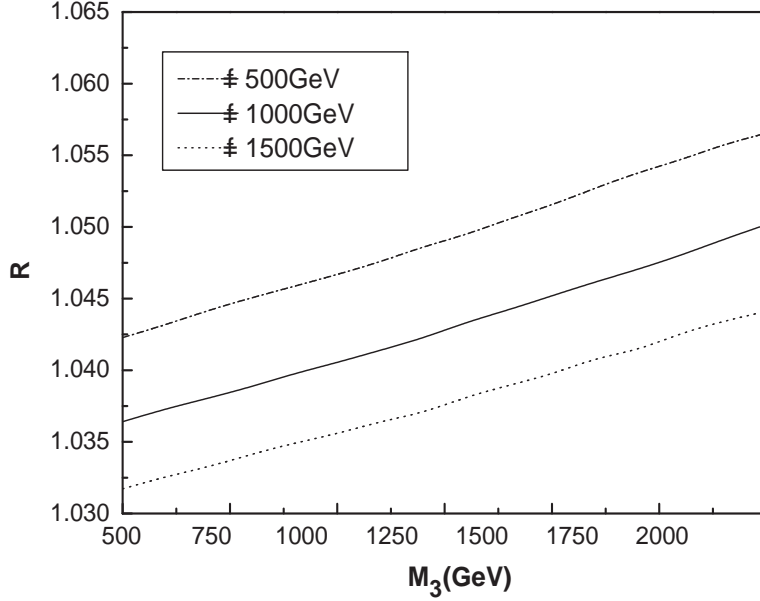


Figure 7: In case I, the charge asymmetry parameter R as a function of the mass parameter M_3 for $M_1 = M_2 = 300\text{GeV}$ and three values of the scale parameter f .

The new parameters in the LHT model are the scale parameter f , the mixing parameter X_L , the mirror fermion masses, and the mixing matrices V_{Hd} and V_{Hl} . The masses of the T -odd gauge bosons W_H^\pm, Z_H , and A_H can be fixed by the scale parameter f . The parameter X_L describes the mixing between the T -even heavy top quark T_+ and the top quark t , and its value is in the range of $0 \sim 1$. Since X_L contributes the coupling tqg at least at order of ν^2/f^2 , we fix its value as 0.5. The masses of the mirror leptons and the mixing matrix V_{Hl} are not related our calculation. For the masses of the mirror quarks,

there is $M_{U_H^i} = M_{D_H^i} = M_i$ at $O(\nu/f)$. The mixing matrix V_{Hd} can be parameterized by three mixing angles $\theta_{12}^d, \theta_{23}^d, \theta_{13}^d$ and three irreducible phases $\delta_{12}^d, \delta_{23}^d, \delta_{13}^d$ [26]. The mixing matrix V_{Hu} can be determined by $V_{Hu}^\dagger V_{Hd} = V_{CKM}$.

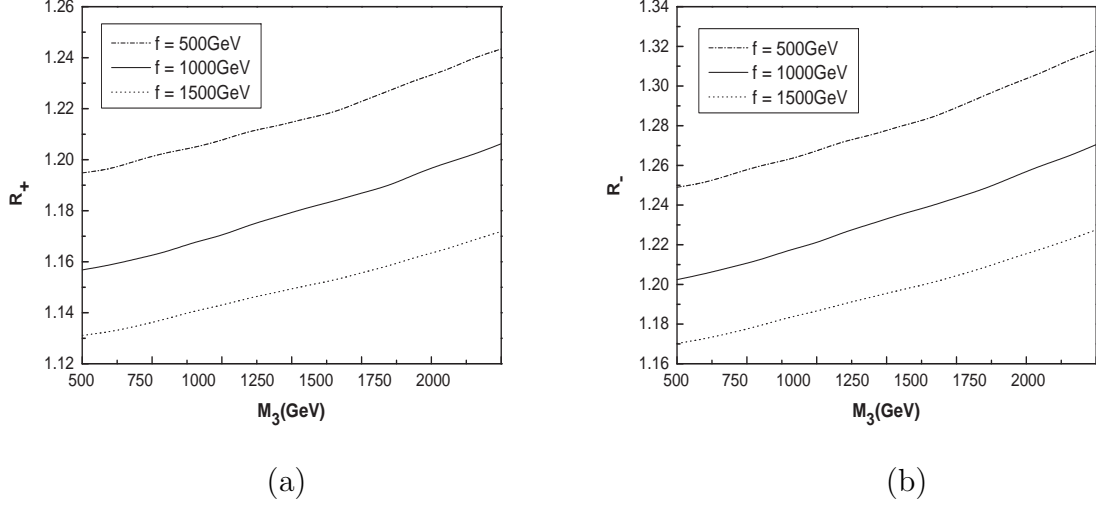


Figure 8: Same as Fig.6 but for case II.

Refs.[21, 22, 26, 27] have studied the impact of the *LHT* dynamics on the *K*, *B*, and *D* systems in considerable detail. They have shown that the *LHT* model can produce potentially sizable effects on the relative observables and its free parameters should be constrained. To simplify our calculation, in this paper, we only consider two scenarios for the structure of V_{Hd} , which can easily escape these constraints,

Case I: $V_{Hd} = I$, $V_{Hu} = V_{CKM}^\dagger$,

Case II: $S_{23}^d = 1/\sqrt{2}$, $S_{12}^d = S_{13}^d = 0$, $\delta_{12}^d = \delta_{23}^d = \delta_{13}^d = 0$.

In both above cases, the constraints on the mass spectrum of the mirror quarks are very relaxed. So we assume $M_1 = M_2 = 300\text{GeV}$ and the mass M_3 of the third generation mirror quarks in the range of $500\text{GeV} \sim 2000\text{GeV}$. For the scale parameter f , we take its typical values, i.e. $500\text{GeV} \sim 2000\text{GeV}$.

The parameters R_+ , R_- , and R contributed by the anomalous top couplings t_{cg} and t_{ug} in the *LHT* model are plotted as functions of the mass parameter M_3 for the *c.m.*

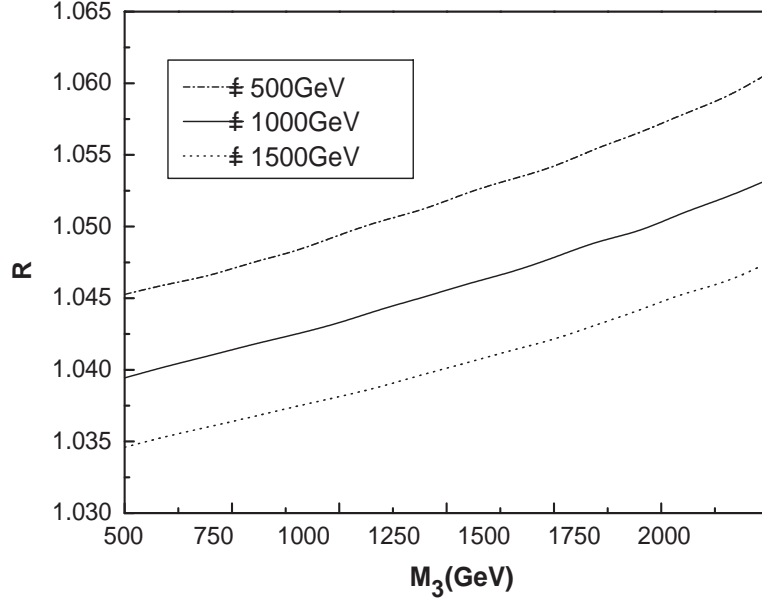


Figure 9: Same as Fig.7 but for case II.

energy $\sqrt{s} = 14 TeV$ and three values of the scale parameter f , which are shown in figures 6 \sim 9. From these figures one can see that the contributions of the anomalous top coupling tqg induced by the *LHT* model to the tW production process are generally larger than those for the *TC2* model. This is partly because the contributions of the *LHT* model from the anomalous top couplings tcg and tug , while only from the anomalous top coupling tcg for the *TC2* model. The values of the parameters R_+ , R_- , and the deviation $\delta R = R_- - R_+$ increase as the mass parameter M_3 increases, which is because the couplings between the mirror quarks and the *SM* quarks are proportion to the mirror quark masses. So the parameter R also increases as M_3 increases. Certainly, compared to the parameters R_+ and R_- , R is insensitive to the mass parameter M_3 and its values are only in the ranges of $1.042 \sim 1.056$ and $1.045 \sim 1.061$ for case I and case II, respectively. These parameters also depend on the parameterization scenarios of the matrix V_{Hd} . Their values for case II are generally larger than those for case I. In most of the parameter space of the *LHT* model, the values of the relative correction parameters R_+ and R_- are larger than 1.1.

Thus, the correction effects of the anomalous top coupling tqg induced by the LHT model on the tW production cross section might be detected at the LHC . Although the value of the charge asymmetry parameter R induced by the LHT model is larger than that for the $TC2$ model, its value is smaller than 1.06. So, observing the charge asymmetry of tW production at the LHC induced by the LHT model is much challenge.

4. Conclusions

The tW production process is one of important single top production channels at the LHC . In the SM , the production cross sections of single top quark and single anti-top quark in the tW channel are equal, i.e. $R = \sigma(tW^-)/\sigma(\bar{t}W^+) = 1$. However, the anomalous top coupling tqg can generate contributions to the cross sections $\sigma(tW^-)$ and $\sigma(\bar{t}W^+)$, and further give rise to the charge asymmetry. If the correction effects of the new coupling tqg on the tW production channel are observed at the LHC , it will be helpful to test the flavor structure of the SM and further to probe new physics beyond the SM .

The $TC2$ model and the LHT model are two kinds of popular new physics models, which can generate the anomalous top coupling tqg . In the context of the $TC2$ and LHT models, we consider the correction effects of the new coupling tqg on the tW production channel at the LHC with the *c.m.* energy $\sqrt{s} = 14TeV$. Our numerical results show that they can indeed generate significant contributions to the tW production process. The contributions of the anomalous top coupling tqg induced by the $TC2$ model to the tW production process are generally smaller than those for the LHT model. With reasonable values of the free parameters for the LHT model, its corrections to the production cross sections of the processes $pp \rightarrow tW^- + X$ and $pp \rightarrow \bar{t}W^+ + X$ can reach 32% and 24%, respectively. The value of the charge asymmetry parameter $R = \sigma(tW^-)/\sigma(\bar{t}W^+)$ can reach 1.06.

The $TC2$ model and the LHT model can modify the Wtb coupling and further produce correction effects on the tW production cross section [28, 29]. However, their contributions to the production cross section of the process $pp \rightarrow tW^- + X$ are equal to those for the

production cross section of the process $pp \rightarrow t\bar{t}W^+ + X$. Thus, such modification about the Wtb coupling can not cause the charge asymmetry in the tW production process at the LHC .

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